

Testing the initial conditions and dynamical evolution of star clusters using Gaia - I

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ABSTRACT

We investigate how the properties of escaping stars are related to the initial conditions of their birth clusters. We find that the number of escaping stars, their spatial distribution, and their kinematics show a dependence on the initial conditions of the host cluster (substructure and virial ratio). Thus the properties of escaping stars can be used to inform us of the initial conditions of star formation, and also provide a window into the dynamical history of star clusters. The ESA Gaia mission will make observations of the positions and proper motions of these escaping stars at the required accuracy to allow us to investigate the dynamical evolution of local star clusters and provide an important insight into the initial conditions of star formation.

Key words: kinematics and dynamics - open clusters and associations: general

1 INTRODUCTION

How stars form is one of the outstanding questions in astronomy. In particular, it is not clear if stars typically form in clusters (e.g., Lada & Lada 2003), in particular in a quasi-static way (Tan et al. 2006), or form in a hierarchical distribution (Gutermuth et al. 2005; Bressert et al. 2010) which can then violently dynamically evolve into dense star clusters (Allison et al. 2009, 2010; Portegies Zwart et al. 2010). Dynamical interactions rapidly erase initial substructure and any memory of the initial conditions, and so deducing the initial conditions from dynamically evolved clusters and distinguishing these possibilities is difficult.

Constraining the initial conditions of star clusters is important as their initial state directly influences the early dynamical evolution of the cluster, such as its ability to remove any initial structure (Goodwin 1998; Goodwin & Whitworth 2004; Smith et al. 2011), dynamically mass segregate (Allison et al. 2009, 2010; Moeckel & Bonnell 2009a; Moeckel & Bate 2010), and process its binary population (Kroupa 1995; Parker et al. 2009, 2011; Moeckel & Bate 2010). However, it is difficult to distinguish between a cluster that has evolved dynamically to be, for example, mass segregated, and one which was mass segregated at its formation (primordial). Therefore it is important to be able to estimate whether a cluster is dynamically evolved or not; but this is difficult to measure as most potential indicators of dynamical evolution (e.g. mass seg-

regation) can have a primordial origin. Escaping stars, however, offer a unique measure of the past dynamical state of a star cluster. Clusters with a violent past could be distinguishable from clusters with a relatively quiet history from their escaper population.

The ESA Gaia mission will conduct an all-sky astrometric and spectrophotometric survey of $\sim 10^9$ point sources between 6th and 20th magnitude. The Gaia mission will be able to measure the distance, position and velocity distribution of the local Galactic stellar population to high accuracy. Therefore Gaia will not only find co-moving groups of stars (dispersing clusters), but it will be able to identify escaping stars from clusters and measure their velocities at large (angular and physical) distances from their birth cluster.

In this letter we show how escaping stars might be used to investigate the dynamical history of star clusters and the conditions of their formation. In Section 2 we describe our initial conditions for relatively active and relatively quiet clusters. In Section 3 we show that the escaper populations from the two clusters are very different and that these differences should be observable by Gaia. We discuss the implications in Section 4, before concluding in Section 5.

2 INITIAL CONDITIONS

We perform N -body simulations of young star clusters with two different sets of initial conditions. The initial conditions are designed to produce one class of cluster that undergoes rapid and violent dynamical evolution, and another class that has a relatively quiescent dynamical history. However,

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both produce a central ‘cluster’ that appear very similar to one another after a few Myr.

The initial conditions vary the initial amount of structure and the initial virial ratio. The initial spatial distribution of stars is created by using a fractal distribution, as described in detail in Goodwin & Whitworth (2004). Using a fractal distribution allows a simple procedure with which structured distributions can be created and reproduced. The method also benefits from having only a single parameter to control the amount of substructure – the fractal dimension (D). The fractal dimension parameterises the structure such that a lower value implies more substructure (i.e. more clumpy), and $D = 3.0$ is a random distribution. The initial velocities are set as described in Allison et al. (2010) and are scaled to a global virial ratio (Q). We define the virial ratio as $Q = T/|\Omega|$ (where T and Ω are the kinetic and potential energies of stars, respectively), such that a virialised cluster has $Q = 0.5$.

In this study we investigate the effect of initial structure and virial ratio on the properties of escaping stars. We present two different initialisations: 1) an initially cool and highly structured cluster ($D = 1.6$, $Q = 0.3$); and 2) an initially virialised and less structured cluster ($D = 2.6$, $Q = 0.5$), labelled $D1.6Q0.3$ and $D2.6Q0.5$, respectively. Each simulation contains 1000 stars, has an initial maximum radius of 1 pc, includes no primordial binaries or gas, and a three-part power law is used for the stellar initial mass function (IMF, Kroupa 2002),

$$N(M) \propto \begin{cases} M^{-0.3} & m_0 \leq M/M_\odot < m_1, \\ M^{-1.3} & m_1 \leq M/M_\odot < m_2, \\ M^{-2.3} & m_2 \leq M/M_\odot < m_3, \end{cases} \quad (1)$$

with $m_0 = 0.08 M_\odot$, $m_1 = 0.1 M_\odot$, $m_2 = 0.5 M_\odot$ and $m_3 = 50 M_\odot$. No stellar evolution is included because of the short duration of the simulations (~ 4 Myr). We use the STARLAB N -body integrator KIRA to run our simulations (Portegies Zwart et al. 2001). We analyse 50 realisations for each initial condition.

For this initial study we have simplified the initial conditions. Complications such as initial binaries, tidal fields, natal gas, etc have been ignored to allow a simple numerical experiment to be performed. We also ignore various observational selection effects and assume perfect knowledge of the four dimensions of phase space that Gaia will best determine, viz. positions on the sky, and proper motions. Gaia itself, as well as follow-up observations will also determine the distance and radial velocities of stars, but to a lower accuracy.

3 THE VARIANCE OF PROPERTIES MEASURABLE BY GAIA

Here we investigate two properties of escaping stars that are measurable by Gaia:

- (i) The number of escaping stars and their spatial distribution around their parent cluster;
- (ii) The kinematics of the escaping stars.

We will show that these properties are dependent on the initial conditions, and therefore contain much information on the initial conditions of star formation.

Escaping stars are defined using three criteria:

- (i) The magnitude of the velocity is greater than the stars current escape speed;
- (ii) The magnitude of the radial component of the velocity vector is larger than the tangential component;
- (iii) The star is outside some ‘escaper’ radius; which is set at two times the half mass radius.

3.1 Spatial distribution of ejected stars

Our two clusters evolve in very different ways for the first 2 Myr. The clumpy and cool cluster ($D1.6Q0.3$) undergoes a dense collapse phase and re-expansion before reaching a Plummer-like equilibrium state by 4 Myr as described in (Allison et al. 2010). The smoother, virialised cluster ($D2.6Q0.5$) gently relaxes to a Plummer-like equilibrium in roughly a crossing time (see also, Allison et al. 2010). The final states of the clusters are illustrated in Figure 1. The left-hand panels show the inner 3 pc radius region of typical examples of the two clusters after 4 Myr, as can be seen the spatial distribution of the two clusters is very similar and memory of their initial conditions has been erased. However, the right-hand panels show the spatial distribution on a 20 pc radius scale in which there is clearly a difference: the $D1.6Q0.3$ cluster having more, and more widely distributed, escaping stars.

Clumpy and cool clusters undergo a much more dynamical evolution and smooth and relaxed clusters. Previous work on the effect of initial spatial distributions has shown that clusters which are initially clumpier tend to have a more violent, dynamical evolution, undergoing mass segregation (Allison et al. 2009, 2010; Moeckel & Bonnell 2009b), forming trapezium-like systems (high-order multiples containing high-mass stars; Allison & Goodwin 2011), and even influencing the binary properties (Parker et al. 2011). In smoother, relaxed clusters these effects are much less pronounced, and it is likely that features such as trapezium systems and mass segregation cannot have a dynamical origin (Bonnell & Davies 1998; Allison et al. 2010) and so must have a ‘primordial’ origin in the nature of star formation itself.

The spatial distribution of stars in the central regions of these initially very different clusters (left-hand plots in Figure 1) show few differences. But if we move out beyond the pc-scale into the 10s pc-scale (right-hand plots) we can immediately observe that these clusters have had a very different dynamical history. Essentially, the differences in the numbers, distance and velocities of escapers is a window into the dynamical history of the cluster. More and faster escapers means that a cluster is dynamically older and has had more two-body encounters within it to eject stars.

The $D1.6Q0.3$ cluster shown in Figure 1 (top panels) has 80 escaping stars as projected on the sky (in three dimensions it has actually 149 escaping stars). This is compared to 15 escapers in projection (30 in three dimensions) for the $D2.6Q0.5$ cluster (bottom panels). These results are typical throughout our ensembles, with clumpy, cool clusters producing an average of 57 escapers, and smooth, relaxed clusters producing only 12 in projection (115 and 20 in three dimensions, respectively).

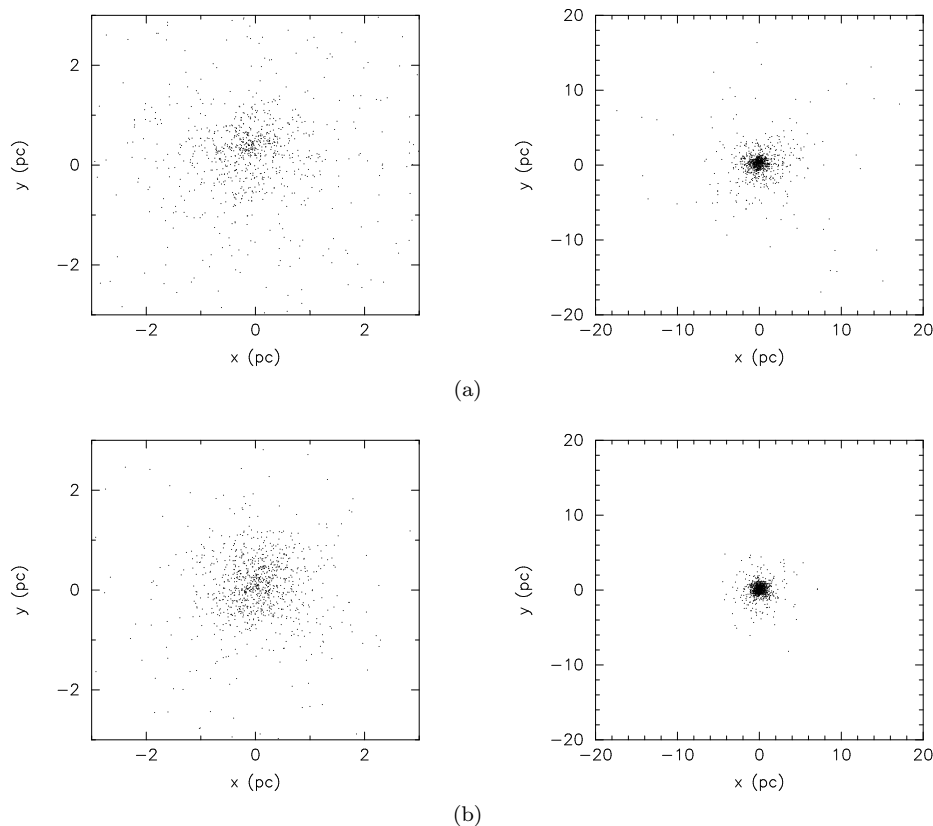


Figure 1. The two-dimensional projection of (a) an initially cool and clumpy cluster ($Q = 0.3$ & $D = 1.6$), and (b) an initially virialised and smoother distribution ($Q = 0.5$ & $D = 2.6$) at 4 Myrs. The plots on the left show the central regions on 2 pc scale, the differences between the spatial distributions are not obvious. However, the right side plots show a zoomed out view (20 pc), here the differences are clear. The initially clumpier cluster has a much more pronounced population of escaping stars, caused by its more energetic dynamical evolution.

3.2 Kinematics

The differences between the spatial distributions of the escaping stars from the two clusters is also seen in the kinematics of their escaping stars. Figure 2 shows the cumulative distribution of the escaping stars from the $D1.6Q0.3$ cluster (black solid line) and the $D2.6Q0.5$ (red dashed line). There is a clear difference between the kinematics of the two sets of escaping stars. The $D2.6Q0.5$ cluster shows a small spread of escaper velocities, with 90 per cent of the ejected stars within a 0.5 km s^{-1} spread around 1.5 km s^{-1} , with a median escaper velocity of 1.2 km s^{-1} . The maximum escaper velocity from this cluster is $< 10 \text{ km s}^{-1}$. While the $D1.6Q0.3$ cluster, has a larger 2 km s^{-1} spread for 90 per cent of escapers (with a median velocity of 2 km s^{-1}), and has a much more pronounced high velocity tail. 10 per cent of escaping stars have velocities over 5 km s^{-1} and the maximum escaper velocity is 15 km s^{-1} .

It should be noted that there is some degeneracy between the distance of an escaping star from the cluster and its ejection velocity which Gaia can break. An ejected star at 10 pc from the cluster may have been ejected 4 Myr ago at 2.5 km s^{-1} , or 1 Myr ago at 10 km s^{-1} . The difference between these two situations is important as a 10 km s^{-1} requires a much stronger interaction (probably with a massive binary) than a 2.5 km s^{-1} ejection event (see below).

The velocity cumulative distribution functions shown

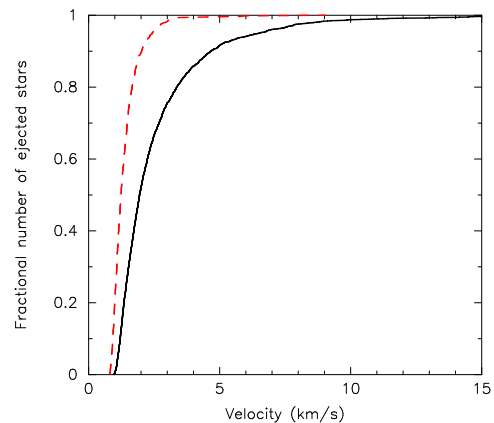


Figure 2. The cumulative distribution function of the velocities of escaping stars for the cool and clumpy (black, solid line) and virialised and smoother (red, dot-dashed line) clusters at 4 Myrs. The differences between the velocity distributions are caused by the dynamical evolution of the clusters. The cool and clumpy cluster is able to produce faster moving escaping stars through its dynamic early evolution and eject stars at high velocities through binary star formation. The virialised smoother cluster has a more quiescent early evolution, and does not produce a population of fast moving escaping stars.

in Figure 2 can be separated into two populations, high- ($\gtrsim 5 \text{ km s}^{-1}$) and low-velocity ($\lesssim 5 \text{ km s}^{-1}$). The high-velocity tail is populated by stars ejected by high-mass binary systems. This population is mostly missing from the *D2.6Q0.5* clusters because they are not able to easily form these binary systems (the clusters are initially single stars). While the more dynamic early evolution of the *D1.6Q0.3* clusters allows the formation of high-mass binary systems (e.g., Allison & Goodwin 2011). In clusters with a primordial binary population the formation of high-mass binary systems is easier, as forming binaries through dynamics is a difficult process (Kroupa 1995).

If primordial massive binaries are present then a high-velocity tail should also be present even in quiescent clusters, although we would still expect a smaller number of ejections as the number of encounters with the massive binary should be lower (due to the younger dynamical age of the quiescent cluster). We will return to this in a later paper when we examine the effect of primordial binaries.

4 DISCUSSION

We have investigated the influence of the initial conditions of star cluster on the properties of escaping stars. We have shown that after 4 Myr of evolution clusters with very different initial conditions in both substructure and virial ratio appear to have similar spatial distributions on pc-scales. However, on larger scales ($\sim 10\text{pc}$) the spatial distributions of the clusters are very different (Figure 1). Clusters which are initially cool and clumpy have significantly more escaping stars, and these escapers have a higher average velocity, and a pronounced high-velocity tail (Figure 2). Therefore, one can learn about the dynamical evolution and initial conditions of star clusters, by observing the population of escaping stars around star clusters.

Disentangling the effects of dynamical evolution and birth properties in star clusters is a complex problem. For example, can one use young star clusters ($< 1 \text{ Myrs}$) to investigate the primordial binary population? Dynamical simulations have shown that star clusters process their primordial binary population as they dynamically evolve, therefore it is important that we are able to estimate how *dynamically evolved* a cluster is if we are to infer information about its primordial state. However, can we distinguish between a primordial binary population that *looks* dynamically processed and a population that actually has been? Likewise with mass segregation - how does one distinguish between ‘primordial’ and dynamical mass segregation? Clearly, dynamical mass segregation *must* only occur in dynamically evolved clusters (as this occurs on the relaxation timescale). Therefore, mass segregated clusters that are not dynamically evolved but are mass segregated are *primordially* mass segregated.

Measuring the true dynamical age of a star cluster is difficult. Clusters such as the Orion Nebula Cluster have *current* relaxation times of $\sim 50 \text{ Myrs}$, which implies that they are dynamically very young, having an age $\approx 1/10$ its relaxation time. However, dynamical simulations have shown that current cluster timescales can be misleading. Clusters that undergo an initial collapse and re-expansion have had much shorter relaxation times in their past, and can therefore be dynamically more evolved than they appear when

using their current relaxation times (Bastian et al. 2008; Portegies Zwart & Chen 2008; Allison et al. 2010).

Escaping stars are therefore a very useful population to investigate, as they are dynamical in origin - there is no obvious primordial process that would produce a significant population of escaping stars from a cluster. Thus, measuring the population of escaping stars from a star cluster (and their properties, e.g. velocities) tells us about the dynamical history of the cluster. This work is the first step into looking at how the escaping population is related to initial conditions of star clusters.

Stars that escape from clusters retain information about the dynamical state of the cluster at the time that they are liberated. Thus, the kinematics of escaping stars can provide us with information about the state of their host cluster at the time of their escape. For example, high-velocity escapers are an indication of either the formation of a binary or an interaction with one. The kinematics of a star ejected by a binary can inform us of the properties of the binary, and the velocity and distance of the escaping star allow us to constrain a time at which the interaction occurred (see e.g., Tan 2004; Zapata et al. 2009). In particular, examining the high-velocity escapers produced by interactions with massive binaries and Trapezium-like systems may constrain the formation time of those systems and distinguish between primordial and dynamical models for their formation.

The Gaia mission provides the first opportunity to examine the dispersed population around star clusters. As it is all-sky it will find stars at great (angular) distances from clusters and the additional kinematic and distance information provided will allow stars to be associated with their birth cluster even if they have travelled a large distance on the sky.

What we have not addressed in this letter are the observational limitations of the Gaia data. Sky position and proper motions will be obtained to an accuracy of positions and proper motions are expected to be $\sim 200 \mu\text{arcseconds}$ and $\sim 150 \mu\text{arcseconds}$, respectively, for 20th magnitude objects (Lindgren 2010). This means that Gaia will have accurate positions and proper motions for G-dwarfs at 1 kpc, but for M-dwarfs only out to a few 100 pc. Therefore the masses of escapers from more distant clusters will be an important observational limitation. We will return to this in later work.

5 CONCLUSIONS

We have investigated how the properties of escaping stars are related to the initial conditions of their host clusters. We find that the number of escaping stars and their spatial distribution/kinematics show a dependence on the initial conditions of the host cluster (substructure and virial ratio). Escaping stars from initially cooler and clumpier clusters tend to be more numerous, and have a larger spread in velocities. While virialised and smoother clusters are less efficient at producing escaping stars. These simulations have been carried out with simple initial conditions (i.e. no binaries, gas, tidal fields), although there is no reason to think that the addition of more complex initial conditions/processes will significantly alter the results as the results depend on the dynamical age of the cluster. But following work will inves-

tigate the influence of more complicated initial conditions. The properties of escaping stars can be used to inform us of the initial conditions of star and cluster formation, and can provide us with a window into the dynamical history of star clusters.

The ESA Gaia mission will provide the all-sky coverage and dynamical information required to investigate escaping populations from star clusters and provide an important insight into the initial conditions of star formation.

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